Ecology Letters, (2008) **11**: 1169–1177 doi: 10.1111/j.1461-0248.2008.01226.x

LETTER

The need for speed: informed land acquisitions for conservation in a dynamic property market

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Abstract

Land acquisition is a common approach to biodiversity conservation but is typically subject to property availability on the public market. Consequently, conservation plans are often unable to be implemented as intended. When properties come on the market, conservation agencies must make a choice: purchase immediately, often without a detailed knowledge of its biodiversity value; survey the parcel and accept the risk that it may be removed from the market during this process; or not purchase and hope a better parcel comes on the market at a later date. We describe both an optimal method, using stochastic dynamic programming, and a simple rule of thumb for making such decisions. The solutions to this problem illustrate how optimal conservation is necessarily dynamic and requires explicit consideration of both the time period allowed for implementation and the availability of properties.

Keywords

Biodiversity, conservation planning, decision theory, property market, stochastic dynamic programming, surveying, threatened species.

Ecology Letters (2008) 11: 1169–1177

INTRODUCTION

By explicitly incorporating important conservation objectives and constraints into the decision-making process, systematic conservation planning can effectively prioritize conservation actions (Margules & Pressey 2000). Systematic conservation plans are generally based on the assumption that they can be executed instantaneously (Costello & Polasky 2004). In reality, however, most conservation plans take time to implement, during which the value or availability of conservation actions may also change (Knight & Cowling 2007). The dynamic nature of biodiversity assets, costs and land tenures demand a dynamic approach to conservation planning (Possingham & Wilson 2005). Recent advances include the incorporation of expected decline or improvement in the biodiversity value under different future scenarios (Drielsma & Ferrier 2006; Strange *et al.* 2006), dealing with budgetary constraints and the scheduling of conservation actions (Costello & Polasky 2004; Meir *et al.* 2004; Wilson *et al.* 2007), the application of temporal management instruments on private land (Knight 1999; Newburn *et al.* 2005) and methods of dealing with the processes important for biodiversity persistence (Bengtsson *et al.* 2003; Drechsler & Watzold 2007; Knight & Cowling 2007; Pressey *et al.* 2007).

In regions governed by strong private property rights and tenure, land acquisition by conservation agencies is often spatially and temporally limited by the availability of land parcels. At any given time, the availability of a land parcel will depend on factors outside the agency's control, such as landholders' willingness to sell (Knight & Cowling 2007). The issue of parcel availability is particularly important for smaller conservation organizations: their resources are severely limited and they have no legislative power with which to influence the availability of land parcels (e.g. eminent domain/expropriation). Options for acquisition are mostly restricted to purchasing parcels that have been put up for sale voluntarily (Binning 1997; Pence *et al.* 2003; Merenlender *et al.* 2004). Several practical decision rules have been modelled and tested to help achieve systematic conservation goals in a landscape where the availability of land parcels is outside an agency's control: 'opportunistic land purchasing' (Meir *et al.* 2004; Turner & Wilcove 2006). By incorporating the capacity for opportunism, these prioritization rules allow conservation planning to proceed, even where implementation of these plans is unlikely to be instantaneous. However, these rules are restricted in assuming that once an appropriate land parcel comes on the market, it will be purchased. They do not consider other important and practical issues relevant to conservation investors, such as the option of waiting for potentially better parcels to come on the market, or the need to spend time and money surveying the biodiversity assets of a parcel before a purchase is made.

Where conservation plans are executed over a period of time, a choice will often exist between acquiring a currently available land parcel now, or gambling on a better land parcel becoming available in the future. As conservation agencies are generally under pressure to take measurable action, either within a specified funding period, or before donors or governments lose interest, waiting for a better parcel carries the risk that no better parcels become available before the funding period ends. Similarly, if an agency decides to spend time surveying an available parcel to determine its biodiversity value before purchasing it, there is no guarantee that the parcel will remain available on the market for the entire time it takes to survey. The question of whether to buy now or wait fits within the broader economic framework of Search Theory (Stigler 1961; Reinganum 1982; Ferguson 1989). A common application of Search Theory is the 'job search' problem (McCall 1970), from labour economics. In this situation, an unemployed worker, who has some idea of the salaries they will be offered, must decide when it is optimal to take a currently advertised job, rather than remaining unemployed in the hope that a higher paid position becomes available. Land acquisition for conservation is analogous to this problem, with the decision about whether to purchase a land parcel replacing job acceptance.

Although conservation managers routinely make intuitive decisions about whether to purchase or wait, this decision has rarely been formalized in conservation theory. Possingham *et al.* (1993) described a method to incorporate availability of land parcels into a decision-making framework, deriving a dynamic model for designing protected areas. Similarly, Haight *et al.* (2005) examined a decision-making process for the protection of open-space in metropolitan areas that allows for uncertainty in the future availability of sites, which are not purchased immediately. Although these two papers attempt to maximize species representation across purchased areas, they assume that the potential reward of all land parcels is known. Our model expands on this work in a novel and pragmatic direction; incorporating not only site availability but also uncertainty in the reward obtained from land purchases. We further extend this area of research by investigating the influence of time limitations on decision-making – how a finite funding period affects both the optimal investment strategy and the likely reward.

To illustrate this problem, we describe a common scenario where an agency, such as a governmental department or Non-Governmental Organization (NGO), has to purchase a property within a fixed time period to designate as a new conservation area. The length of the funding period may not be as inflexible as a government term, but we assume that donors or governments will not allow agencies to delay indefinitely. In our example, the biodiversity reward of a parcel is defined by the number of nationally threatened species persisting there, a metric that is part of the decision-making process for many conservation-focused organizations (Environment Australia 2001). Thus the agency's objective is to maximize the number of nationally threatened species protected within the new conservation area. Due to a lack of political leverage, the agency in question must rely on purchasing a land parcel that is publicly available on the real estate market. As properties become available, the agency must decide between three actions: (i) buy the property immediately without full knowledge of the threatened species present; (ii) survey the property to determine the exact number of threatened species before making a decision about purchase; or (iii) do not purchase but instead wait, in the hope that a property with a greater number of threatened species becomes available in the future. To illustrate this scenario, we use information on land acquisition by The Department of Environment and Heritage in South Australia (DEHSA). Stochastic dynamic programming (SDP) is used to determine whether an agency should take, leave or survey a newly available parcel. This optimization includes two decisions not considered by the current dynamic land acquisition literature: the option of waiting and the option of gathering more information. We also derive a simple rule of thumb that calculates the optimal acceptability threshold. Although this rule of thumb does not perform as well as the optimal solution, it offers a straightforward strategy based on current knowledge and the time before an agency must make a decision.

METHODS

Problem definition

We assume that the conservation agency has been allocated resources that must be spent by the end of a funding period of length T. The funds are sufficient to purchase a single land parcel. Throughout the funding period, individual parcels of land become available for purchase on the market at fixed time intervals of length t (e.g. one parcel per year for 5 years: $t = 1$, $T = 5$). We do not incorporate variation in the cost of each land parcel, simply assuming that the allocated budget is only sufficient to purchase a single parcel. The agency cannot save money for use in subsequent funding periods, so the cost of individual parcels does not explicitly enter the decision-making process.

Although the exact set of threatened species present on each parcel is initially unknown to the agency, managers

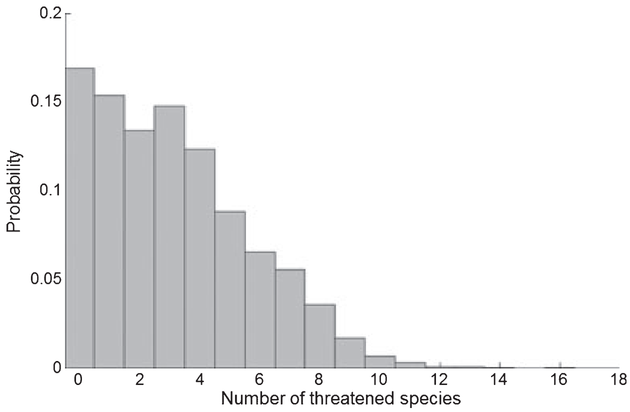

Figure 1 Frequency distribution of the number of threatened species on parcels of land in South Australia (derived from species of national significance dataset: Commonwealth of Australia 1999).

have information on the predicted spatial distribution of each threatened species, which can be distilled into a probability distribution, $f(x)$, of the number of threatened species, x, likely to be in any given parcel (Fig. 1).

When a new parcel comes on the market, managers are faced with two decisions: (D1) purchase, without knowing the exact number of threatened species present; or (D2) wait, and survey the parcel to determine exactly how many are present. If they decide to survey, there is a probability, δ, that the parcel may be taken off the market during the surveying process (e.g. purchased by another buyer), and thus will not be available for acquisition once the surveying process is complete. If the parcel surveyed previously remains on the market, a third decision is available: (D3) purchase the surveyed parcel, which contains a known number of threatened species, x_s. The manager must decide whether x_s is acceptable, given that a superior parcel may become available in the future. If the manager decides that the surveyed parcel is not sufficiently valuable and declines to purchase, the parcel will be taken off the market, and cannot be purchased in subsequent time steps.

This process continues until the agency either purchases a parcel (exhausting their budget) or until the final step of the funding period is reached. If no parcel has been purchased before this time, the manager is able to purchase the penultimate parcel surveyed (assuming it was not purchased during the survey process), or alternatively they must buy the parcel of unknown biodiversity reward that is offered in the final time step.

The manager's decision to wait and survey, or to purchase the known parcel will obviously depend on the time remaining in the funding period. Towards the end of a funding period, the opportunities for getting a better parcel become fewer. The decisions faced by the agency are thus dynamic in nature; to find the optimal strategy, we must consider the temporal aspect of land availability, in addition to the market volatility.

Optimization procedure

We use SDP to determine dynamic decision rules that will maximize the expected number of threatened species protected. The use of SDP enables all possible futures to be considered; it is based on a state-dependent model of the system that incorporates time (Bellman 1957; Mangel & Clark 1988). SDP determines which decision is optimal given the distributions of threatened species, the quality of the surveyed parcel, the time remaining in the funding period and the probability a parcel will be removed from the market during a survey. The method works by stepping backwards in time from the end of the funding period, T, where a terminal reward, R is received. To evaluate which decision is optimal, SDP requires the definition of system states, transition probabilities between these states, each state's reward and an overall objective (McCarthy *et al.* 2001).

States

The system has $S = 2(x_{\max} + 1)$ total system states, where $x_{\max}$ is the maximum number of threatened species in our distribution (Fig. 1). Each state, i, corresponds to a particular combination of two variables: (i) whether a parcel has been purchased ($b = 1$ if purchased, $b = 0$ if not) and (ii) the number of threatened species in the most recently surveyed parcel, x_s, such that:

$$i = b(x_{\max} + 1) + x_s + 1. \tag{1}$$

Transitions

Given each of the three decisions, k, we need to define the probability of transitioning between each system state, which we store in a set of transition matrixes, M_k, where $M_k(i,j)$ contains the probability that the system transitions from state i to state j, if decision k is implemented.

If the manager decides to purchase the parcel of unknown biodiversity reward, the transitions are:

$$M_1(i,j) = \begin{cases} 1, & \text{if } i > x_{\max} + 1, j = i, \\ f(j - x_{\max} - 2), & \text{if } j > x_{\max} + 1, i \le x_{\max} + 1, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Once a purchase is made, the system remains in the same state through subsequent time steps (case 1 above – this holds for each of the transition matrices). If no land parcel has been purchased, our new state will involve going from a state where no purchase has been made ($i \le x_{\max} + 1$) to a state where a parcel has been purchased ($j > x_{\max} + 1$), according to the probability distribution of threatened species (case 2).

If managers choose to wait and survey, D2, then the transitions are:

$$M_2(i,j) = \begin{cases} 1, & \text{if } i > x_{\max}+1, j = i, \\ \delta + (1-\delta)f(0), & \text{if } j = 1, i \le x_{\max}+1, \\ f(j-1)(1-\delta), & \text{if } j \le x_{\max}+1,\ i \le x_{\max}+1, \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

Prior to purchase, surveying can result in two events. In case 2, surveying reveals zero threatened species, either because the parcel is removed from the market during survey (δ), or because the surveyed parcel contains no threatened species ($(1-\delta)f(0)$). In case 3, surveying uncovers a valuable parcel that is not taken off the market.

The transition matrix corresponding to purchasing a known parcel is:

$$M_3(i,j) = \begin{cases} 1, & \text{if } i > x_{\max}+1, j = i, \\ 1, & \text{if } i \le x_{\max}+1 \text{ and } j = i + x_{\max}+1, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Case 2 indicates that the purchase of a parcel with a known number of threatened species simply changes b from 0 to 1 (eqn 1).

Objective

The objective of this decision-making procedure is to acquire a parcel with the greatest number of threatened species, by the end of the funding period. At the terminal time, the reward in each state is defined by the number of threatened species in the purchased parcel:

$$R(i,T) = \begin{cases} i - x_{\max} - 2, & \text{if } i > x_{\max}+1, \\ 0, & \text{if } i \le x_{\max}+1. \end{cases} \tag{5}$$

By stepping backwards through time, Bellman's principle states that the optimal outcome will maximize the expected reward at each time step (Bellman 1957). The strategy that will achieve this is defined by the dynamic programming equation:

$$R(i,t) = \max_{k \in 1,2,3} \left\{ \sum_{j=1}^{S} M_k(i,j) R(j, t+1) \right\}. \tag{6}$$

Defining probability of loss

The probability of a parcel being removed from the market during surveying, δ, is constructed from the approximate time required for a detailed biodiversity survey (organization of staff, permits, actual survey time etc.), t_s, and the probability of a parcel being taken off the market, $p(t)$, at any point during that time. We assume that the probability of being taken off the market is uniform, and bounded between zero and the maximum time a parcel can be on the market, t_m ($p(t) \sim [0, t_m]$). The probability δ is therefore:

$$\delta = \int_{0}^{t = t_s} p(t) = \min\left[\frac{t_s}{t_m}, 1\right]. \tag{7}$$

South Australian land acquisition case study

DEHSA acquires approximately one parcel of land for conservation purposes annually (T. Hills, pers. comm.). We assume that the agency is allocated resources for a funding period of 12 months, and needs to acquire one parcel of land at some point during this period. Although DEHSA may consider up to 20 parcels throughout the year for purchase (T. Hills, pers. comm.), this will not always be the case. As a conservative estimate, we assumed that one parcel of land becomes available every month. The probability distribution of the number of threatened species likely to be present on a parcel is derived from species of national significance dataset (Commonwealth of Australia 1999 Fig. 1).

It takes *c.* 30 days for DEHSA to implement a detailed survey of a parcel (t_s = 30; T. Hills, pers. comm.), and a parcel remains on the market in rural South Australia for *c.* 60 days (Elders Real Estate SA, pers. comm.). This average time implies a uniform distribution bounded at 120 days (t_m = 120). Based on eqn 7, the probability that DEHSA lose a parcel during surveying is 0.25.

Deriving a static rule

The optimal acquisition strategy provided by SDP depends on both the time remaining in the funding period and the biodiversity reward of the available land parcel. Unfortunately, the mathematical complexity of the method often limits its utility for managers. One simple alternative is to use a simple decision threshold. For example, a static rule might be that a manager accepts a minimum percentile, A (e.g. A = 0.1 indicates that the manager will accept any parcels with a biodiversity reward in the top 10% of all parcels). Over a large number of repetitions, managers who follow rule A should expect to get a parcel with a particular biodiversity reward, X. This value depends on the overall distribution of threatened species in parcels, $f(x)$, the length of the funding period, T, and the expected value of parcels that managers following rule A are prepared to accept, that is:

$$\mu_2 = \frac{\sum_{x=B}^{\infty} x f(x)}{\sum_{x=B}^{\infty} f(x)}, \tag{8}$$

where B is the minimum number of threatened species that the managers following rule A are prepared to accept. Thus, we choose B such that the absolute value of $A - \sum_{x=B}^{\infty} f(x)$ is minimized.

The probability of a manager not being offered an acceptable parcel, in a single time step, is a combination of the probability of not being offered a parcel with sufficient threatened species, and the probability of losing an acceptable parcel during the survey process. Thus, the expected value of X for a particular static strategy A is:

$$E[X(A)] = \mu_1[(1-A) + \delta A]^{\mathrm{T}} + \mu_2(1 - [(1-A) + \delta A]^{\mathrm{T}}), \quad (9)$$

where the first term represents those occasions where no acceptable parcels become available throughout the entire time period and the second term represents outcomes where an acceptable parcel was purchased. By taking the derivative of this function with respect to A, equating this to zero and numerically solving for A, we can find the static decision that gives the maximum expected value of X – the 'optimal static rule'.

Using forward simulations (repeated 50 000 times), we compare the mean number of threatened species contained in parcels as a result of purchasing under our static rule, with the outcome of using the optimal strategy from the SDP solution. We also investigate the distribution of the parcels purchased under both methods.

RESULTS

At each time step, SDP calculates which of our three options is optimal (Fig. 2). Purchasing a parcel of unknown biodiversity reward (D1) is only ever optimal in the last month of the funding period, when no time remains for surveying. However, even in this final time step, this decision is only optimal if the parcel of known value is removed from the market, or has fewer threatened species than the regional average (Fig. 2). If the surveyed parcel was still on the market, and had more threatened species than the regional average, then the best decision was to purchase this parcel (D2).

In all other circumstances, it is optimal to purchase the parcel surveyed in the previous month (D2) or wait and survey the new parcel that has become available on the market (D3). Intuitively, as the number of time steps remaining decreases, managers should accept parcels with fewer threatened species, rather than waiting for a better parcel that is increasingly unlikely to become available. The form of this relationship depends on the probability of a parcel remaining on the market at the completion of surveying, δ (Fig. 3). If this probability of removal is low, a surveyed parcel has a higher chance of remaining available

Figure 2 Optimal decision space for purchasing land parcels based on the data shown in Fig. 1 and a loss rate δ = 0.25. The conservation system state is further defined by the number of threatened species of the known parcel surveyed in the previous time step and the time remaining in the funding period. For each system state, the optimal decision is indicated by the square colour. Light grey indicates that the manager should purchase the surveyed parcel if it remains on the market. Medium grey indicates that the manager should not purchase the surveyed parcel, and wait for a better one. Dark grey indicates that the manager should not purchase the surveyed parcel, and instead immediately purchase the unknown parcel.

for purchase in the next month, and consequently, managers will wait for a parcel with more threatened species.

To be useful, a static rule of thumb needs to provide managers with outcomes comparable to the optimal dynamic strategy. In general, our static rule of thumb results in the purchase of parcels with fewer threatened species than the SDP solution (Fig. 4). However, purchasing with the static rule of thumb still results in parcels with significantly more threatened species than random purchases. The difference in performance between the static rule of thumb and SDP solution is on average 9.62 percentile points but this difference is lower for shorter funding periods (Fig. 4). While the optimism of the static rule of thumb does reflect the number of opportunities available to the manager (through the variable T, eqn 9), its consistently suboptimal performance relative to the SDP highlights how important it is to change conservation decisions (and to become more risk averse) as deadlines approach and options narrow.

While the percentile difference provides a general picture of the difference in performance between the rule of thumb and the optimal strategy, its aggregated nature hides more subtle differences. When the two methods are repeatedly applied, the resulting distributions of biodiversity outcomes show a more complex picture (Fig. 5). Critically, the

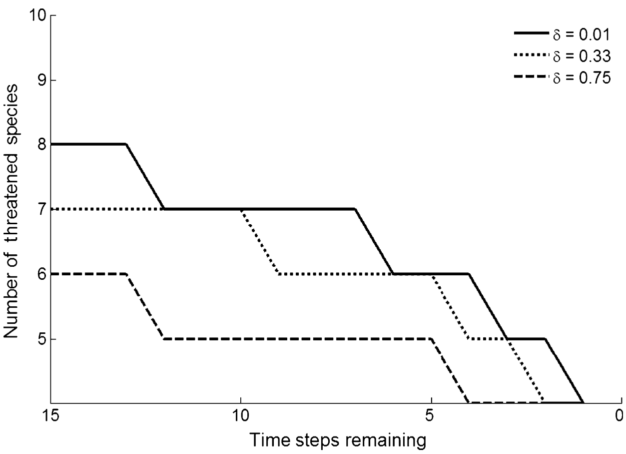

Figure 3 The lowest acceptable number of threatened species of a parcel that should be purchased given the time remaining in the funding period. Each line represents a different probability of losing the parcel from the market.

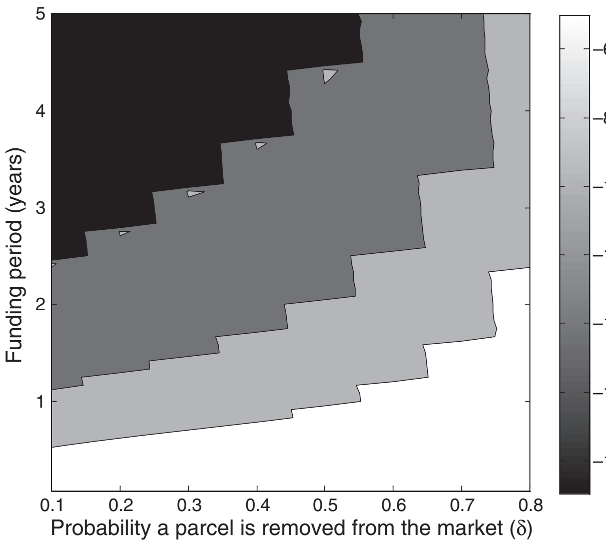

Figure 4 The performance of the rule of thumb compared with the optimal strategy using stochastic dynamic programming, measured by the percentile difference of the parcel purchased. This figure indicates how this relative performance depends on the length of the funding period, T, and the probability of the parcel being removed from the market whilst surveying, δ.

variance around the expected outcome is much greater when using the static rule of thumb, due to a long tail on the lower reward side of the mean. Occasionally, the static rule of thumb purchases parcels with greater reward than would be expected using the optimal solution, but this is outweighed by the risk of purchasing a parcel with very few threatened species. Although simple to implement, the rule of thumb is less reliable in its outcomes than the SDP.

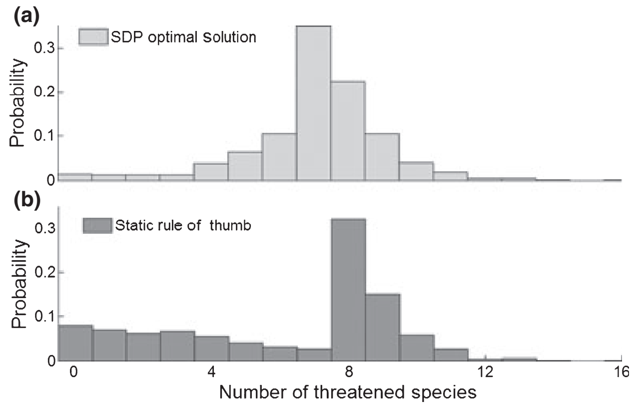

Figure 5 Distribution of number of threatened species purchased using (a) the optimal strategy and (b) the static rule of thumb. These results are based on the same data as Fig. 2.

DISCUSSION

We do not mean to imply that conservation agencies are ignoring temporal factors when making decisions. Managers acquiring sites for conservation are likely to be more selective during the early months of the funding period, and become more conservative when they have few opportunities remaining. Their assessment of a parcel's biodiversity reward would be in reference to the distribution of potential future acquisitions, and they will be concerned with the probability of losing the opportunity to purchase a particular parcel if they delay decisions. Nonetheless, large gains in conservation effectiveness stand to be made if conservation agencies explicitly and mathematically weigh up these competing factors when deciding on conservation investments.

Applying rigorous decision theory analysis to the acquisition process elucidates how decisions and likely rewards will respond to changes in key parameters. These responses not only simply determine the optimal decision in different circumstances, but are also an important source of insight into rarely explored elements of current conservation planning approaches. The most important parameter, the source of both opportunity and risk in decision-making, is the length of time remaining in the funding period. Our results clearly indicate that, when acting optimally, conservation agencies should become more conservative as the final period approaches and should accept parcels with lower, but guaranteed, biodiversity rewards. Such increasing conservatism may result in managers rejecting a parcel of high biodiversity reward in the early stages of a funding period, only to later accept a parcel of lower biodiversity reward. The SDP solution acknowledges this risk, but has determined that it will result in superior expected outcomes.

The benefits of longer funding periods can be interpreted as justification for greater temporal freedom in resource allocation for conservation. Although some organizations are restricted by a set time in which to purchase a land parcel, almost all will be under pressure to spend their budgets in short time frames, to satisfy government-funding bodies or to maintain the interest of donors.

Simply increasing funding periods, however, will not necessarily result in better conservation outcomes. Delays in conservation action as a result of increased funding periods may incur opportunity costs (Fuller *et al.* 2007), either through system-wide declines in biodiversity in the absence of protection or through delaying subsequent actions. Similarly, the gain in expected biodiversity reward as a function of increased purchase opportunities will be subject to diminishing returns: initial increases in funding period length will deliver substantial gains in expected reward, leaving little room for improvement. Acquiring the best possible parcels (which are scarce) can only be achieved with unfeasibly long funding periods. The best outcomes will therefore be achieved if funding periods allow managers a few opportunities to purchase each budgeted parcel.

The factors that affect a manager's biodiversity reward can be divided into those that they can influence and those they cannot. For example, the probability that a property will be taken off the market during surveying will depend, to some extent, on the choice of technique used to measure the biodiversity reward of a parcel. Decisions regarding this technique will most likely be within the control of individual conservation managers. On the other hand, the length of the funding period and the biodiversity reward distribution of parcels will be fixed externally. The length of the period is effectively set exogenously (e.g. by funding bodies, or the upper management of an organization) and cannot be directly altered by the manager. Lobbying for increases in funding periods may not be within the scope of individual conservation projects but can be addressed by higher hierarchical levels within an agency. Relaxation of these limitations could be driven by funding organizations themselves to improve the efficiency of their conservation spending.

The probability that a parcel is taken off the market during the survey, δ, has a considerable impact on the optimal management decision. This removal rate defines the confidence that managers have of being able to make an informed conservation decision in the future. As mentioned earlier, this removal probability will be tied not only to market volatility, but also to the time required to survey a parcel. Lower probabilities of removal from the market allow managers to be more selective about parcels offered earlier in the funding period (Fig. 3). Faster assessments may decrease the probability of removal, and thus increase the probability of purchasing high-value parcels. However, this improvement assumes that gains in speed are based on advances in surveying techniques – rapid assessment techniques that sacrifice accuracy for speed will not necessarily improve outcomes. Even if the risk of a parcel being removed from the market during surveying is zero (e.g. if it is not on the public market, or some purchase option is paid in advance), agencies restricted to a single purchase within a funding period must still decide between purchasing the surveyed parcel or waiting for a potentially better parcel in the future.

Although we do not explicitly consider the impact of potential market price movements on the optimal acquisition strategy, market value is intimately related to the market's volatility, and thus to δ. Increasing land prices can be driven by increasing demand and, in such situations, parcels will spend less time on the market. With adequate knowledge, it is possible to incorporate expected market movements into SDP. If demand for land does increase and parcels have a greater probability of being taken off the market during surveying (eqn 7), a more conservative approach to land acquisition would probably become optimal. An agency may also decide not to purchase early in the funding period but instead invest the budget with the explicit intention of increasing the capital available for land purchase at the end of the funding period. We did not consider these factors in our case study, as DEHSA are unlikely to be free to invest their budget elsewhere, and the benefits of investment and interest gain in the short funding period are likely to be negligible relative to the price of land. However, for conservation NGOs, investment strategies could potentially increase budgets if the length of funding periods makes this option feasible.

The available budget is assumed to be enough to purchase one parcel during the funding period. The existence of a budget constraint does, however, mean that some properties may be too expensive to purchase. If the asking price is known, then properties beyond the budget can be excluded from consideration. If the purchase price is uncertain (e.g. if the property is auctioned), this cost variation could be incorporated into decision-making probabilistically, if it can be parameterized. Managers may also be able to purchase multiple parcels, which would add further complexity to the decision-making process. An explicit budget would need to be defined, and the biodiversity reward of parcels would need to be assessed relative to their cost. An explicit budget raises the possibility of trade-offs between spending money on faster surveys, but potentially fewer purchases.

In the land acquisition problem solved here, the conservation value of each parcel is considered independently, without considering whether species present are already protected in other regions. Conservation agencies, however, often desire new parcels with attributes that complement their existing portfolio (Margules & Sarkar 2007). In many circumstances, this sort of spatial prioritization will take place at a larger scale and results in setting objectives within a particular region. In others, however, it may be necessary for agencies to filter potential properties based on their contribution to broader conservation targets. Although it would be computationally demanding, complementarity could be included in an expanded SDP optimization (e.g. Costello & Polasky 2004).

Although DEHSA's distribution of threatened species is similar to the uncertain state of knowledge for many conservation agencies, it is also possible that conservation agencies have absolutely no knowledge of how biodiversity rewards are distributed within their region. Instead, they may have less certain information, based on random samples of parcels in the region. They may even be entirely ignorant. Such severe uncertainty does not invalidate the approach presented here and indeed could be incorporated using, for example, an information gap theory approach (Ben-Haim 2001). Our understanding of how to act given incomplete knowledge could also be approached using a Bayesian SDP (Regan *et al.* 2006), where additional information is incorporated (e.g. the quality of the parcels that have already been surveyed) and can refine the optimal acquisition strategy.

Decisions regarding land acquisition in conservation are unfortunately subject to the vagaries of the property market and the limitations of funding periods. These constraints make it difficult for conservation agencies to decide whether to purchase an available parcel, or wait for better opportunities. By formulating this problem mathematically, we not only provide an optimal strategy, but also gain insight into the roles of three crucial temporal elements of conservation decision-making: the length of funding periods, the speed of conservation surveys and the volatility of market opportunities. An explicit consideration of these three factors will lead to more confident land purchasing and better outcomes for conservation.

ACKNOWLEDGEMENTS

We would like to thank T. Hills (DEHSA) and P. Taylor (Elders Real Estate, South Australia) for the information needed to complete the South Australian case study. This work came out a workshop on monitoring in conservation planning funded by the Applied Environmental Decision Analysis Centre, a Commonwealth Environment Research Facility Hub. E.M.'s PhD studentship was supported by the Invasive Animals CRC within the Detection, Prevention and Mitigation Program and by a MYQRS scholarship from the University of Queensland. We thank three anonymous referees for their comments on this manuscript.

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Editor, Helen Regan
Manuscript received 13 February 2008
First decision made 21 March 2008
Second decision made 28 May 2008
Manuscript accepted 10 June 2008